Status of the Development of a 128×128 Microshutter Array

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ABSTRACT

We are developing a lithography process for a two-dimensional array of microshutters which can be used as a high efficiency, high contrast field selection device for a multi-object spectrometer for the Next Generation Space Telescope (NGST). The device is a close-packed array of shutters with an individual shutter size of $100\,\mu$m square and area filling factor of about 80%, produced in a $100\,\mu$m thick silicon wafer. Our current array size is 128×128. Each shutter made of silicon nitride with an appropriate optical coating, pivots on a torsion flexure along one edge. A CMOS circuit embedded in the frame around the shutters allows individual selection. An original double-shutter mechanism is employed for actuation. Processing includes anisotropic back etching for wafer thinning, a DRIE back etch through the silicon to the mechanical active nitride membrane and a RIE to produce the shutters out of the nitride membrane. Our layout is based on a detailed mechanical analysis for which we determined crucial material parameters experimentally.

Keywords: microshutters, micro-optics, spatial light modulator, programmable masks, slit mask, DRIE, micromirrors, arrays

1. BACKGROUND

Among the most important applications of Micro Electro Mechanical Systems (MEMS) in optics, are array devices that allow for the redirection of light by individually controllable structures. Developments in this field have been progressing at a fast pace. Most of the research programs are concentrated on micromirrors.[1–3] An alternative approach to light manipulating devices are microshutter arrays. Although advantages of the shutters for applications requiring high-contrast imaging are obvious, there was little done to develop such devices.[4,5]

In astronomical applications micromirror and microshutter devices can be used as object selection devices for multi-object spectrometers. The Next Generation Space Telescope (NGST) gave a strong boost to these studies.[6] Primary wavelength region of NGST operation is the near-infrared, and devices have to be cooled to cryogenic temperatures, which makes technological problems yet even more complex. Two teams are currently developing micromirror arrays for the NGST.[7,8]

Transmissive masks provide lower diffracted and scattered light and as a result achieve higher contrast than reflective devices. Therefore we decided to pursue the goal of creating large fully addressable microshutter arrays of small elements ($100\,\mu$m typical dimension) with high efficiency (80% or better for the ratio of shutter area to the total area). These microshutters are being developed as cryogenic temperature devices for the Multi-Object Spectrometer (MOS) on the NGST. They can also be used at optical wavelengths on ground-based telescopes and other applications where programmable field selection devices are required. Projection technique is one of the potential areas of application. Mass-spectroscopy and laser ranging are other potential applications. In mass-spectroscopy microshutters can be efficiently used for modulation of the ion source. Microshutters can be used for fast changing attenuation of lasers that would help to expand the distance range in LIDAR devices.

Microshutters, unlike micromirrors, require large angles of rotation of the individual microelements. This makes the implementation of a high performance microshutter array challenging. In micromirror arrays the area behind the mirrors is available for the structures that provide actuation and addressing, whereas in a microshutter design all these should be hidden in tiny support structures between the blades and/or on the blades themselves.
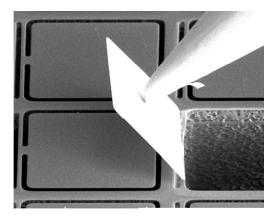
Figure 1. Image of a single microshutter (left) and of a shutter opened with a needle (right).

We have previously developed a design that allows to achieve these goals, have demonstrated the basic concepts and have carried out experiments that suggest that the challenging material requirements that arise out of the concepts can be met by commonly used MEMS materials..[9–11]

In this publication, we present a successful demonstration of a 3×3 array actuation, our concept for addressing and the status of lithographically produced arrays.

2. MICROSHUTTER DESIGN

In our design the individual shutters are about $90\,\mu$m $\times$ $90\,\mu$m in size and can be flexed 90 degree out of the plane of the array on a thin torsion bar. Shutterblade and torsion bar are made out of the same material. They are supported by a silicon grid, about $100\,\mu$m thick with less than $10\,\mu$m wide beams.(Fig. 1, Fig.3)

For large flexing angles a thin layer of a strong material is required. We have demonstrated that $2\,\mu$m silicon and $0.5\,\mu$m silicon nitride are suitable. As there are large stresses induced in the torsion bars during flexing the mechanical analysis of the design and material tests for strength and fatigue form a major part of our study.[12] Latest results are presented in a companion paper.[11]

These shutters have to be packed into a dense array with filling factor around 80%. To do so a unique actuation scheme was developed. This so-called double-shutter actuation allows translating macro-motion of a large structure, the membrane itself, into micro-motion of the shutters. To implement this, two identical microshutter arrays are rotated 180 degrees with respect to each other and brought in close physical contact. Addressing and selecting is performed electronically by applying a voltage between a shutter blade and its counterpart on the actuation membrane (Figure 2). Once blades are selected and engaged actuators located outside of the active area move the whole actuation membrane and all engaged shutters open. De-selection will cause an open shutter to return back into the closed position. Note that to have one pixel on the array open, two neighboring shutters must be actuated.

Addressing will be accomplished dynamically by a DRAM type circuit, addressing one microshutter at a time. To do so a single FET will be placed on the shutter support grid, on the intersections next to each shutter. Column and row select lines will run along the support grid. Each engaged shutter can be considered as a tiny capacitor. Once it is charged by the addressing circuit and disconnected, the deposited charge will be holding the blades attracted to each other. We expect the hold time of the shutters to be long enough to have an acceptably low refresh rate. Multiplexing and dynamic addressing will greatly reduce the complexity of the embedded circuit.

It is important to point out that of the two shutter arrays in the double-shutter configuration only one needs the circuit the second array requires only a metal layer on the back side.
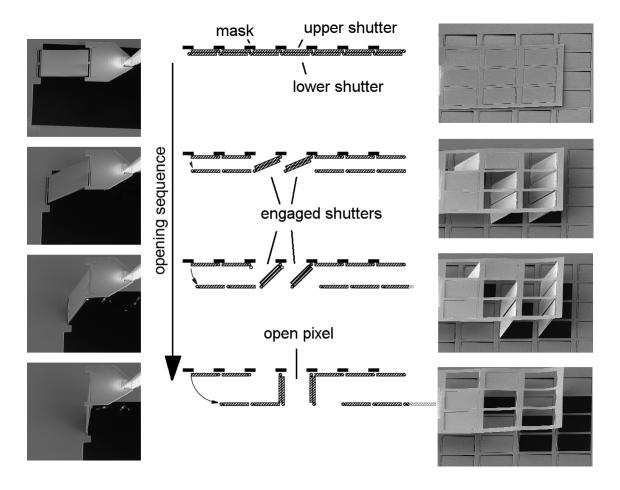
Figure 2. Doubleshutter actuation mechanism: left: single shutter demonstration, center: schematic presentation, right: 3×3 shutter array demonstration. The sequences on the left and right were produced with samples in a SEM with the upper shutters welded to a manipulator needle by ion induced MOCVD. The samples were produced by focused ion beam milling. The sample on the left is produced from a $2\,\mu$m silicon membrane and had a one sided chromium layer of about $20\,$nm, the samples on the right from $0.5\,\mu$m silicon nitride with a one side aluminum layer of about $20\,$nm.

In the double shutter configuration two blades are engaged to have one pixel open. Shutters first are brought to close contact, and a voltage is applied to engage the shutters. The upper shutter is moved along the arc formed by the radius vector connecting their torsion bars.

3. EXPERIMENTS AND TESTS

3.1. Setup

Unlike most of the MEMS devices that involve multiple layer deposition and structuring processes, the microshutter concept is based on one homogeneous layer of high strength material, patterned and used as a mechanically active layer. That makes it possible to follow two major routes in investigating the proposed structures:

For rapid prototyping of shutter and test structures we machine previously backetched membranes in a Focused Ion Beam (FIB) milling machine. We use a FEI 620 at the Laboratory for Ion Beam Research and Application (LIBRA), University of Maryland. This is a dual beam machine, with an ion and electron column, which allows ion milling and situ scanning electron microscopy. It can be used for ion induced Metal Organic Chemical Vapor Deposition (MOCVD) and has a manipulator needle mounted to a 3d piezo stage installed so that it also can be used
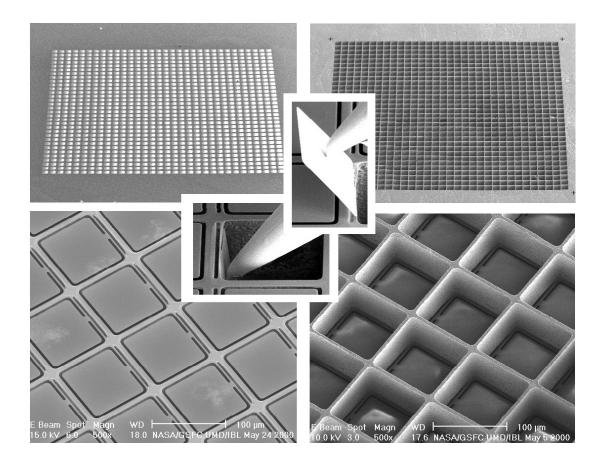
Figure 3. Examples of etched microshutter arrays. The arrays in the figure are 32×32 arrays. The left side shows the front, the right side shows the back of an array. The straight sidewalls of the silicon support grid are well visible in the lower right. In the center insert, shutters were manipulated with a needle to demonstrate that they can move freely and that they survive large deflections.
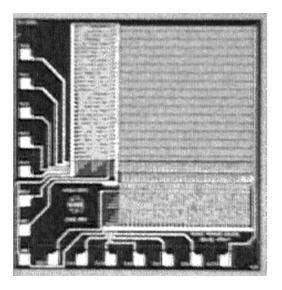
to observe microstructures, to analyze material properties and to mechanically test different designs.[12] This setup allowed very quick turnaround in tests of single shutters and small arrays.

Once basic questions about the structures are answered a lithography process is developed utilizing the capabilities of the Detector Development Laboratory at NASA Goddard Space Flight Center. Deep Reactive Ion Etching (Deep RIE, or DRIE, also called Inductive Coupled Plasma (ICP) etching) in a STS Advanced Silicon Etch (ASE) system is a crucial technology for the microshutter development.

3.2. Current Development Status

Figure 2 shows the results of our rapid prototyping efforts: Starting with anisotropically backetched membranes we first demonstrated single shutter actuation. The image sequence in Fig.2 left side shows a double shutter ion milled from $2\,\mu$m silicon with a chromium layer of about $20\,$nm. Both shutters were etched from the same membrane, then one shutter on a support structure was welded (by ion induced MOCVD) to a tungsten manipulator needle, then released from the membrane. The membrane with the leftover shutter was rotated by 180 degrees and brought into closed contact to the shutter on the needle. A voltage of $30\,$V was applied between the two and the shutter on the membrane moved in an arc to open both shutters. The same procedure was used to create the image sequence on the right side of Figure 2. Instead of silicon, a $0.5\,\mu$m thick layer of low stress CVD silicon nitride was used. Electrical connections to the shutters not to be actuated were cut by ion milling. A 3×3 array was welded to the needle and a 5×5 array in the remaining membrane was used.

Although these test allowed us to demonstrate that both materials are strong enough to be used in the proposed design and that a relatively low voltage is sufficient to hold the shutters together during actuation, they did not
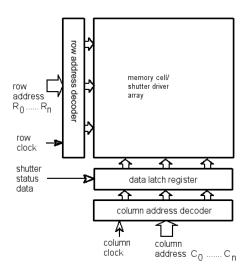
Figure 4. Microshutter DRAM: At the left an image of a 32×32 array similar to what will be used for the microshutters. The presented device has been fabricated at the Detector Development Laboratory at GSFC. The right shows a schematic of the approach for the microshutter DRAM.

represent a viable geometry for an array larger than a few shutters square. Such an array needs a support structure. The etching of such a structure with sufficient front to back side alignment accuracy and sufficient wall steepness represents a crucial step on the way to a lithographically produced array.

The process starts with a $100\,\mu$m silicon wafer with low stress silicon nitride on the front side waxed to a quartz carrier wafer. After a deep reactive ion backetch to the silicon nitride, which serves as the etch stop, the wafer was released from the carrier wafer, the remaining membrane patterned and the shutter structures etched by Reactive Ion Etching. Figure 3 shows some results from this process. We have produced several arrays of different size.

The support grid can be etched with sufficient alignment accuracy and wall stepness. Shutters turn out flat and torsion beams strong enough for rotations beyond 90 degree. Arrays larger than 32×32 showed a nonuniformity in the back etch depth from array edge to array center. We are currently working to solve this problem by modifying the DRIE recipe.

The analysis of break tests on silicon nitride test sample on the etched wafer gave a strength of about $7\,$GPa. According to finite element analysis of the torsion structures stresses of $2\,$GPa are expected in the beams. We expect that the strength of the silicon nitride is sufficient for an acceptable yield of working shutters.[11]

A process sequence has been defined that will allow to integrate CMOS electronics with microshutters. Processing will start with a $400\,\mu$m thick wafer with an oxide etch stop at $100\,\mu$m and a low stress silicon nitride coating. CMOS fabrication will be the first part of the processing, followed by the etching of the shutters, wafer thinning and the DRIE backetch as the final step. The register and decoder layout will be similar to those developed and fabricated at the Detector Development Laboratory at NASA GSFC for a micromirror device. Figure 4 shows an image of a 32×32 address circuit that was produced and the basic concept of the layout. The layout of the transistors for the individual shutters on the intersection of the support grid is close to being finished.

A concept has been developed for a translation mechanism that allows the upper and lower shutter array elements to move with respect to each other by the required 90 degree with a radius of $100\,\mu$m while constraining motion in other degrees of freedom to less than 2% of the total motion. The mechanism will consist of two orthogonal linear flexure stages driven by electromotors and with capacitive feedback sensors. One stage will be driven as a sine, the other as a cosine to generate a circular arc. Figure 5 shows our first layout for such a stage for arrays up to 512×512 without the motors. This layout was designed for high stiffness in order to establish the requirements for the accuracy of motion for later designs that will be of smaller size.
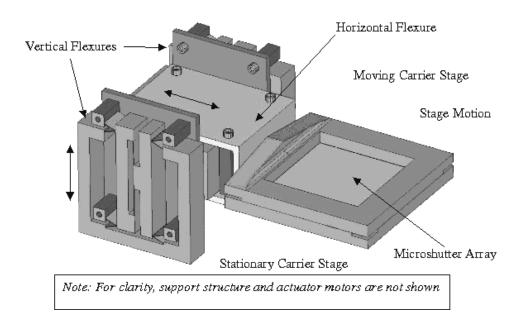
Figure 5. Planned suspension and translation mechanism for a microshutter array in double-shutter configuration.

4. FUTURE WORK

Next steps in our work will be the integration of the CMOS DRAM in the process and the production and full cryogenic testing of an array with 128×128 shutters of which a subarray of 32×32 will be addressable. These tests will be followed by a fully functional 512×512 array for application in a ground based telescope. With shutter sizes in the range of 100 μm, 512×512 is the largest array size that can fit on a four inch wafer. We therefore plan to develop the 2048×2048 for the NGST MOS as a mosaic of 16 512×512 arrays with only thin support frames between the arrays. Figure 6 shows the concept of such a mosaic.

5. SUMMARY

The device being developed in this project will be a large format mask for astronomical multi-object spectroscopy. Major achievement from the technological point of view is the solution of the large deflection angles problem and a close-packed array of elements. Combination of the double shutter actuation scheme with electronic addressing allows random shutter access. Since our device works in transmission, it achieves minimal scattered light and maximum possible contrast of the spectra. Although being designed for a specific goal in the infrared spectroscopy, these devices can find much wider application in such areas as projection technique, laser ranging and mass-spectroscopy. We have successfully demonstrated the design concept on small size shutter arrays (3×3). First photolithographically produced shutter arrays 32×32 prove the feasibility of the process and DRIE in application to it in particular. Our study of the mechanical properties of the materials used also showed the feasibility of the approach.

ACKNOWLEDGMENTS

Shutter
Blade

Silicon Membrane

Torsion
Beam

2 mm
Frame

51 mm
Shutters

2 mm
Frame

20 of 512
Shutters

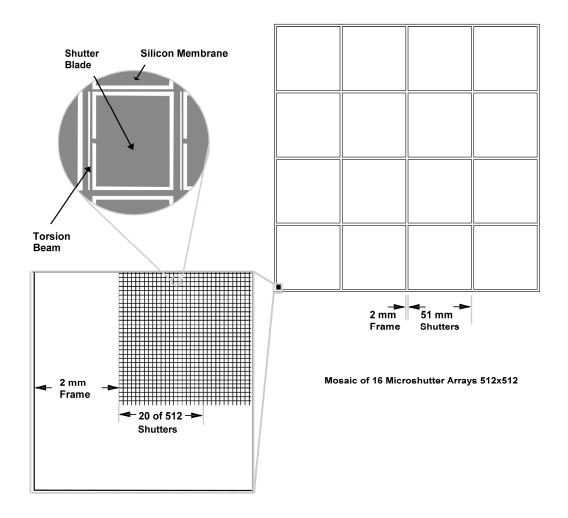**Mosaic of 16 Microshutter Arrays 512x512**

Figure 6. Concept for the future development of a 2048×2048 microshutter array.

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